Solid State Division

Thyristors Application Note AN-4242

A Review of Thyristor Characteristics and Applications

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Thyristors, both SCR's and triacs, are now widely accepted in power-control applications. With the emphasis in such applications placed on low cost, small package size, and circuit simplicity, thyristors satisfy these requirements with reliability exceeding that of electromechanical counterparts. This Note describes the operation, ratings, characteristics, and typical applications of these devices.

Types of Thyristors

Thyristors are semiconductor devices that have characteristics similar to those of thyratron tubes; more specifically, they are semiconductor switches whose bistable state depends on the regenerative feedback associated with a p-n-p-n structure. Basically, this group includes any bistable semiconductor device that has three or more junctions (i.e., four or more semiconductor layers) and can be switched from a high-impedance (OFF) state to a conducting (ON) state, and from the conducting (ON) state to the high-impedance (OFF) state, within at least one quadrant of the principal-voltage characteristics.

There are several types of thyristors, which differ primarily in number of electrode terminals and operating characteristics associated with the third quadrant (negative) of the voltage-current characteristics. Reverse-blocking triode thyristors, commonly called silicon controlled rectifiers (SCR's), and bidirectional triode thyristors, referred to as triacs, are the most popular types. Silicon controlled rectifiers have satisfied the requirements of many power-switching applications with much greater reliability than electromechanical or tube counterparts. As the use of SCR's in power applications increased, the need for complete ac control became apparent. The new family of thyristor devices generated to provide bidirectional current properties is referred to as triacs. A triac can be considered as two parallel SCR's (p-n-p-n) oriented in opposite directions to provide symmetrical bidirectional characteristics.

Two-Transistor Analogy

The bistable action of thyristors can be explained by analysis of the structure of an SCR. This analysis can be related to either operating quadrant of a triac because a triac is essentially two parallel SCR's oriented in opposite directions. A two-transistor analogy of an SCR is illustrated in Fig. 1. Fig. 1(a) shows the schematic symbol for an SCR, and Fig. 1(b) shows the p-n-p-n structure the symbol represents. In the two-transistor model for the SCR shown in Fig. 1(c), the interconnections of the two transistors are such that regenerative action can occur when a proper gate signal is applied to the base of the lower n-p-n transistor.

In the diagram of Fig. 2, the emitter of the upper (p-n-p) transistor is returned to the positive terminal of a dc supply through a limiting resistor R_2, and the emitter of the lower (n-p-n) transistor is returned to the negative terminal of the dc supply to provide a complete electrical path. When the model is in the OFF state, the initial principal-current flow is zero. If a positive pulse is then applied to the base of the n-p-n transistor, the transistor turns on and forces the collector (which is also the base of the p-n-p transistor) to a low potential; as a result, current (I_a) begins to flow. Because the p-n-p transistor is then in the active state,

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collector current ($I_{c1} = I_{b2}$) flows into the base of the n-p-n transistor and sets up the conditions for regeneration. If the external gate drive is removed, the model remains in the ON state as a result of the division of currents associated with the two transistors, provided that sufficient principal current (I_a) is available.

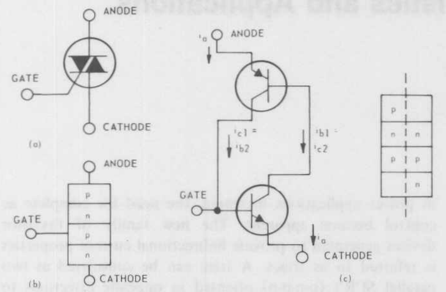

Fig. 1 - Two-transistor analogy of an SCR: (a) schematic symbol of SCR; (b) p-n-p-n structure represented by schematic symbol; (c) two-transistor model of SCR.

Theoretically, the model shown in Fig. 2 remains in the ON state until the principal current flow is reduced to zero. Actually, turn-off occurs at some value of current greater than zero. This effect can be explained by observation of the division of currents as the value of the limiting resistor is gradually increased. As the principal current is gradually reduced to the zero current level, the division of currents within the model can no longer sustain the required regeneration and the model reverts to the blocking state.

The two-transistor model illustrates three features of thyristors: (1) a gate trigger current is required to initiate regeneration, (2) a minimum principal current (referred to as "latching current") must be available to sustain regeneration, and (3) reduction of principal-current flow results in turn-off at some level of current flow (referred to as "holding current") slightly greater than zero.

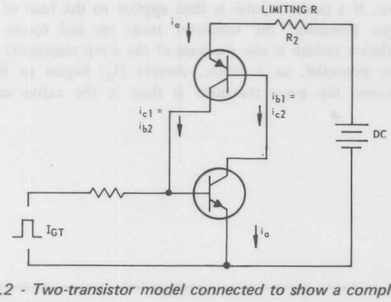

Fig.2 - Two-transistor model connected to show a complete electrical path.

Fig. 3 illustrates the effects on latching and holding current for resistive termination at the base of the n-p-n transistor. The collector current through the p-n-p transistor must be increased to supply both the base current for the n-p-n transistor and the shunt current through the terminating resistor. Because the principal-current flow must be increased to supply this increased collector current, latching and holding current requirements also increase. The use of the two-transistor model provides a more concise meaning to the mechanics of thyristors. In thyristor fabrication, it is generally good practice to use a low-beta p-n-p unit and to include internal resistance termination for the base of the n-p-n unit. Termination of the n-p-n unit provides immunity from "false" (non-gated) turn-on, and the use of the low-beta p-n-p units permits a wider base region to be used to support the high voltage encountered in thyristor applications.

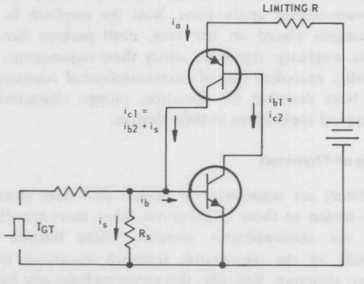

Fig.3 - Two-transistor model of SCR with resistive termination of the n-p-n transistor base.

Voltage and Temperature Ratings

The effects of temperature and voltage are important in thyristors because these devices possess regenerative action and are required to support high voltage in the OFF state. In the two-transistor model shown in Fig. 2, an increase in temperature causes a leakage current which, if allowed to migrate to the base of the n-p-n transistors, forces the transistor into the active region. Regenerative action then calls for additional leakage current, and causes the model to switch into the ON state and establish a principal-current flow. For reliable operation at high temperature, the base of the n-p-n transistor should be terminated with a low value of resistance to prevent turn-on as a result of high-temperature operation.

Because gate termination is required on all thyristors, RCA devices contain a diffused internal gate-cathode resistor (the so-called "shorted-emitter" design) and do not require external gate termination. Therefore, it is not necessary to specify an OFF-state rating under the conditions of external gate-resistance termination. The use of this internal shunt resistance improves the OFF-state blocking capability, provides increased immunity against false turn-on, and slightly increases gate-current requirements.

OFF-state voltage ratings of thyristors are specified for both steady-state and transient operation for both forward (positive) and reverse (negative) blocking conditions at the maximum junction temperature. For SCR's, voltages are considered to be forward (positive) when the anode is at a positive potential with reference to the cathode. Negative voltages are referred to as reverse-blocking voltages. For triacs, voltages are considered to be positive when main terminal 2 is at a positive potential with reference to main terminal 1; this condition is referred to as first-quadrant (I) operation. Third-quadrant (III) operation occurs when main terminal 2 is at a negative potential with reference to main terminal 1. Fig. 4 shows the principal voltage-current characteristics for both SCR's and triacs.

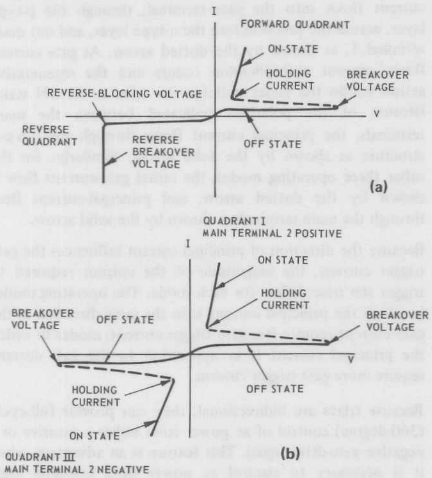

Fig.4 - Principal voltage-current characteristics of SCR's and triacs.

Operation of an SCR under reverse-blocking voltage is similar to that of a reverse-biased silicon rectifier or other semiconductor diodes. In this operating mode, the SCR exhibits a very high internal impedance, and a small reverse current flows through the p-n-p-n structure until the reverse breakdown voltage is reached, at which time the reverse current increases rapidly. For forward (positive) operation, the SCR is electrically bistable and exhibits either high impedance (forward-blocking or OFF state) or low impedance (forward-conducting or ON state). In the forward-blocking state, a small leakage current, considered to be of approximately the same value as that for reverse leakage, flows through the p-n-p-n structure. As the forward voltage is increased, a "breakdown" point is reached at which the forward current increases rapidly and the voltage across the SCR decreases abruptly to a very low voltage, referred to as the forward ON voltage. When the SCR is in the ON state, the forward current is limited primarily by the impedance of the external circuit. Increases in forward (principal) current are accompanied by only a slight change in ON-state voltage.

If the triac is considered as two parallel SCR's oriented in opposite directions to provide symmetrical current flow, the behavior of a triac under positive or reverse voltage operation is essentially the same as that of an SCR in the forward-blocking mode.

Gate Characteristics

The breakover voltage of a thyristor can be varied, or controlled, by injection of a signal at the gate terminal. Fig. 5

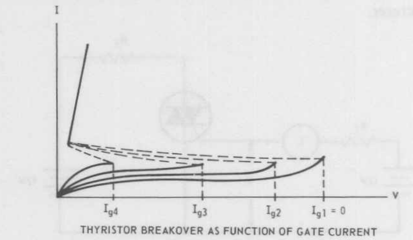

Fig.5 - Thyristor breakover as a function of gate current.

shows curves of breakover as a function of gate current for first-quadrant operation of an SCR. A similar set of curves can be drawn for both the first and the third quadrant to represent triac operation.

When the gate current I_g is zero, the applied voltage must reach the breakover voltage of the SCR or triac before switching occurs. As the value of gate current is increased, however, the ability of a thyristor to support applied voltage is reduced and there is a certain value of gate current at which the behavior of the thyristor closely resembles that of a rectifier. Because thyristor turn-on, as a result of exceeding the breakover voltage, can produce instantaneous power dissipation during the switching transition, an irreversible condition may exist unless the magnitude and rate of rise of principal current is restricted to tolerable levels. For normal operation, therefore, thyristors are operated at applied voltages lower than the breakover voltage, and are made to switch to the ON state by gate signals of sufficient amplitude to assure complete turn-on independent of the applied voltage. Once the thyristor is triggered to the ON state, the principal-current flow is independent of gate voltage or gate current, and the device remains in the ON state until the principal-current flow is reduced to a value below the holding current required to sustain regeneration.

The gate voltage and current required to switch a thyristor from its high-impedance (OFF) state to its low-impedance (ON) state at maximum rated forward anode current can be

determined from the circuit shown in Fig. 6. Resistor R_2 is selected so that the anode current specified in the manufacturer's ratings flows when the device latches into its low-impedance or ON state. The value of R_1 is gradually decreased until the device under test is switched from its OFF state to its low-impedance or ON state. The values of gate current and gate voltage immediately prior to switching are the values required to trigger the thyristor. For an SCR, there is only one mode of gate firing capable of switching the device into the ON state, i.e., a positive gate signal for a positive anode voltage. If the gate polarity is reversed (negative voltage), the reverse current flow is limited by the value of R_2 and the gate-cathode internal shunt. The value of power dissipated for the reverse gate polarity is restricted to the maximum power-dissipation limit imposed by the manufacturer.

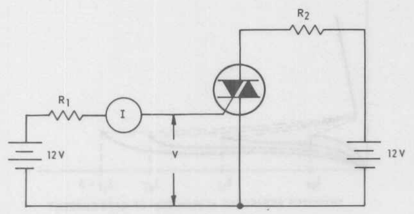

Fig.6 - Circuit used to measure thyristor gate voltage and current switching threshold.

Because of its complex structure, a triac can be triggered by either a positive or a negative gate signal regardless of the voltage polarity across the main terminals of the device. Fig. 7 illustrates the triggering mechanism and current flow within a triac. The gate trigger polarity is always referenced

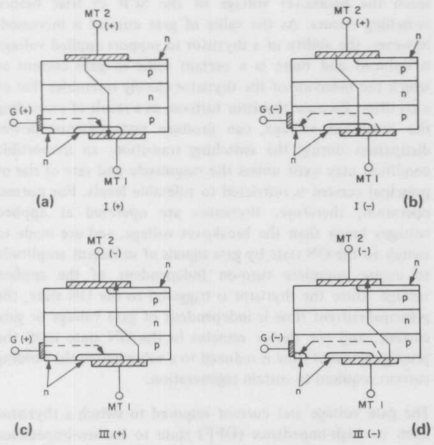

Fig.7 - Current flow in a triac.

to main terminal 1. The potential difference between the two terminals is such that gate current flows in the direction indicated by the dotted arrow. The polarity symbol at main terminal 2 is also referenced to main terminal 1. The semiconductor materials between the various junctions within the pellet are labeled "p" and "n" to indicate the type of majority-carrier concentrations within the material.

For the various operating modes, the polarity of the voltage on main terminal 2 with respect to main terminal 1 is given by the quadrant in which the triac operates (either I or III), and the polarity of the gate signal used to trigger the device is given by the proper symbol next to the operating quadrant. For the I(+) operating mode, main terminal 2 and the gate are both positive with respect to main terminal 1. Initial gate current flows into the gate terminal, through the p-type layer, across the junction into the n-type layer, and out main terminal 1, as shown by the dotted arrow. As gate current flows, current multiplication occurs and the regenerative action within the pellet switches the triac to its ON state. Because of the polarities indicated between the main terminals, the principal current flows through the p-n-p-n structure as shown by the solid arrow. Similarly, for the other three operating modes, the initial gate-current flow is shown by the dotted arrow, and principal-current flow through the main terminals is shown by the solid arrow.

Because the direction of principal current influences the gate trigger current, the magnitude of the current required to trigger the triac differs for each mode. The operating modes in which the principal current is in the same direction as the gate current require less gate trigger current; modes in which the principal current is in opposition to the gate current require more gate trigger current.

Because triacs are bidirectional, they can provide full-cycle (360-degree) control of ac power from either a positive or a negative gate-drive signal. This feature is an advantage when it is necessary to control ac power from low-level logic systems such as integrated-circuit logic. With gate-power requirements for turn-on in the milliwatt region, triacs are capable of controlling power levels up to 10 kilowatts. Thus, the power gain associated with these thyristors far exceeds that of transistor counterparts in the semiconductor switching field.

Like many other semiconductor-device parameters, the magnitude of gate trigger current and voltage varies with the junction temperature. As thermal excitation of carriers within the semiconductor material increases, the increase in leakage current makes it easier for the device to be triggered by a gate signal. Therefore, the gate becomes more sensitive in all operating modes as the junction temperature increases. Conversely, if a triac or SCR is to be operated at low temperatures, sufficient gate trigger current must be provided to assure triggering of all devices at the lowest operating temperature expected in any particular application. Variations of gate-trigger requirements are given in the published data for individual thyristors.

The gate current specified in published data for thyristors is the dc gate trigger current required to switch an SCR or triac into its low-impedance state. For practical purposes, this dc value can be considered equivalent to a pulse current that has a minimum pulse width of 50 microseconds. For gate-current pulse widths smaller than 50 microseconds, the pulse-current curves associated with a particular device should be used to assure turn-on.

When pulse triggering of a thyristor is required, it is always advantageous to provide a gate-current pulse that has a magnitude exceeding the dc value required to trigger the device. The use of large trigger currents reduces variations in turn-on time, increases di/dt capability, minimizes the effect of temperature variation on triggering characteristics, and makes possible very short switching times. When a thyristor is initially triggered into conduction, the current is confined to a small area which is usually the more sensitive part of the cathode. If the anode current magnitude is great, the localized instantaneous power dissipation may result in irreversible damage unless the rate of rise of principal current is restricted to tolerable levels to allow time for current spreading over a larger area. When a much larger gate signal is applied, a greater part of the cathode is turned on initially; as a result, turn-on time is reduced, and the thyristor can support a much larger peak anode inrush current.

Switching Characteristics

Ratings of thyristors are based upon the amount of heat generated within the device pellet and the ability of the device package to transfer the internal heat to the external case. For high-performance applications in which switching of high peak current values but narrow pulse widths is desired, the internal energy dissipated during the turn-on process must be determined to assure that power dissipation is within ratings.

When thyristors (either triacs or SCR's) are triggered by a gate signal, the turn-on time consists of two stages, a delay time t_d and a rise time t_r, as shown in Fig. 8. The total turn-on time t_{gt} is defined as the time interval between the initiation of the gate signal and the time for the principal anode current flow through the thyristor to reach 90 per cent of its maximum value for a resistive load. The delay time t_d is defined as the time interval between the 50-per-cent point of the leading edge of the gate trigger voltage and the 10-per-cent point of the principal current for a resistive load. The rise time t_r is the time interval required for the principal current to rise from 10 to 90 per cent of its maximum value. The total turn-on time t_{on} is the sum of both delay and rise time ($t_d + t_r$).

Although the thyristor is affected to some extent by the peak off-state voltage and the peak on-state current level, the turn-on time is influenced primarily by the magnitude of the gate-trigger pulse current, as shown in Fig. 9. Faster turn-on time for larger gate drive is a result of a decrease in delay

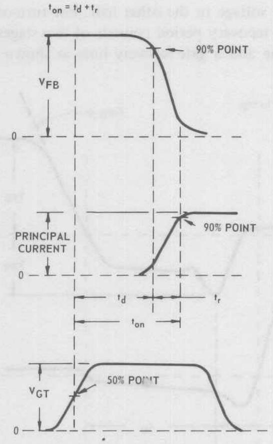

Fig.8 - Waveshapes illustrating thyristor turn-on time.

time associated with the thyristor because of the increased current density at the gate-cathode periphery. Of major importance in the turn-on time interval is the relationship between thyristor voltage and principal current flow through the thyristor. During the turn-on interval, the dynamic voltage drop is high and the current density can produce localized hot spots in the pellet area. Therefore, it is important that power dissipation during turn-on be restricted to levels within device specifications.

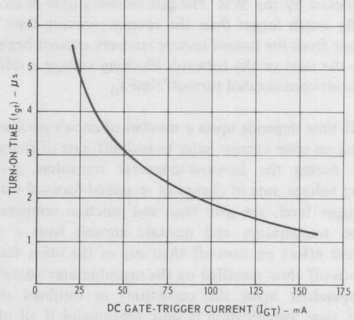

Fig.9 - Thyristor turn-on time as a function of gate trigger current.

Turn-off time of a thyristor can be associated only with SCR's. In triacs, a reverse voltage cannot be used to provide circuit-commutated turn-off voltage because a reverse voltage applied to one half of the triac structure would be a

forward-bias voltage to the other half. For turn-off times in an SCR, the recovery period consists of two stages, a reverse recovery time and a gate recovery time, as shown in Fig. 10.

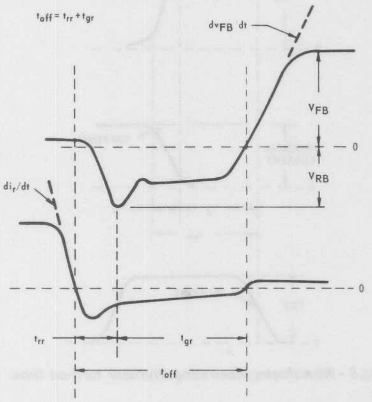

Fig. 10 - Waveshapes illustrating thyristor turn-off time.

When the forward current of an SCR is reduced to zero at the end of a conduction period, application of reverse voltage between the anode and cathode terminals causes reverse current to flow in the SCR until the time that the reverse current passes its peak value to a steady-state level called the reverse recovery time t_{rr}. A second recovery period, called the gate recovery time, t_{gr}, must then elapse for the forward-blocking junction to establish a depletion region so that forward-blocking voltage can be reapplied and successfully blocked by the SCR. The gate recovery time of an SCR is usually much longer than the reverse recovery time. The total time from the instant reverse recovery current begins to flow to the start of the forward- blocking voltage is referred to as circuit-commutated turn-off time t_q.

Turn-off time depends upon a number of circuit parameters, including on-state current prior to turn-off, rate of change of current during the forward-to-reverse transition, reverse-blocking voltage, rate of change of reapplied forward voltage, gate trigger level, the gate bias, and junction temperature. Junction temperature and on-state current have a more significant effect on turn-off than any of the other factors. With turn-off time specified on the manufacturer's data sheet and dependent upon the conditions as outlined above, turn-off time specification is only meaningful if all of the above critical parameters are available in the actual application.

For applications in which an SCR is used to control 60-Hz ac power, the entire negative half of the sine wave is a turn-off condition and more than adequate for complete turn-off. For applications in which the SCR is used to control the output of a full-wave rectifier bridge, however, there is no reverse voltage available for turn-off, and complete turn-off can be accomplished only if the bridge output is reduced to zero volts or the principal current is reduced to a value lower than the device holding current.

Because turn-off times are not associated with triacs due to the physical structure of the device, a new term is introduced called "critical rate of rise of commutation voltage", or the ability of a triac to commutate a fixed value of current under specified conditions. The rating can be explained by consideration of two SCR's in an inverse parallel mode, as shown in Fig. 11. SCR-1 is assumed to be in the conducting state

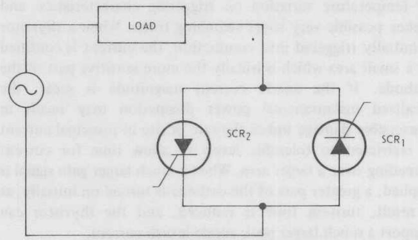

Fig. 11 - Circuit used to demonstrate critical rate of rise of commutation voltage.

with forward current established. As the principal current flow crosses the zero reference point, a small reverse current flows in SCR-1 until the time that the SCR reverts to the OFF state. The principal current is then diverted to SCR-2, provided that sufficient gate current is available to that device.

The structure of a triac shown in Fig. 12 indicates that the main blocking junctions are common to both halves of the

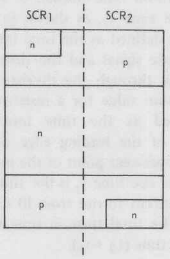

Fig. 12 - Structure of a triac.

device. When the first half of the triac structure (SCR-1) is in the conducting state, a quantity of charge accumulates in the n-type region as a result of the principal current flow. As the principal current crosses the zero reference point, a small

reverse current is established as a result of the charge remaining in the n-type region. Because the n-type region is common to both halves of the devices, this reverse recovery current becomes a forward current to the second half of the triac. The current resulting from stored charge may cause the second half of the triac to go into the conducting state in the absence of a gate signal. Once current conduction has been established by application of a gate signal, therefore, complete loss in power control can occur as a result of interaction within the n-type base region of the triac unless sufficient time elapses to assure turn-off. It is imperative that triac manufacturers provide sufficient information regarding commutating capability under maximum current and case-temperature conditions so that triac control of ac power for resistive loading in a 60-Hz power source can be assured.

Commutation of triacs is more severe with inductive loads than with resistive loads because of the phase lag between voltage and current associated with inductive loads. Fig. 13 shows the waveforms for an inductive load with lagging

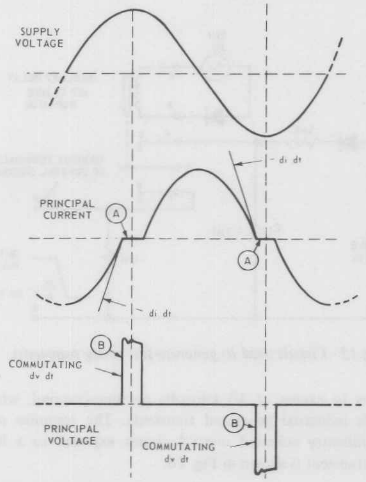

Fig. 13 - Waveshapes of commutating dv/dt characteristics.

current power factor. At the time the current reaches zero crossover (point A), the half of the triac in conduction begins to commutate when the principal current falls below the holding current required to sustain regeneration. Because the high-voltage junction is common to both halves of the triac, the stored charge can be neutralized only by recombination. At the instant the conducting half of the triac turns off, an applied voltage opposite to the current polarity is applied across the triac terminals (point B). Because this voltage is a forward bias to the second half of the triac, the sudden reapplied voltage in conjunction with the remaining stored charge in the high-voltage junction reduces the over-all device capability to support a fast rate of rise of applied voltage. The result is a loss of power control to the load, and the device remains in the conducting state in absence of a gate signal. Therefore, it is imperative that some means be provided to restrict the rate of rise of reapplied voltage to a value which will permit triac turn-off under the conditions of inductive load.

An accepted method for keeping the commutating dv/dt within tolerable levels during triac turn-off is to use an RC snubber network in parallel with the main terminals of the triac. Because the rate of rise of applied voltage at the triac terminal is a function of the load impedance and the RC snubber network, the circuit can be evaluated under worst-case conditions of operating case temperature, maximum principal current, and any value of conjunction angle. The values of resistance and capacitance in the snubber are then adjusted so that the rate of rise of commutating dv/dt stress is within the specified minimum limit under any of the conditions mentioned above. The value of snubber resistance should be high enough to limit the snubber capacitance discharge currents during turn-on and dampen the LC oscillation during commutation (turn-off). Any combination of snubber resistance and capacitance that provides the requirements outlined above is considered satisfactory.

Some of the factors affecting commutating dv/dt capability of triacs are temperature, current magnitude, rate of change of current during commutation, and frequency of the applied principal current. With frequency directly related to commutating di/dt, early triac use was restricted to 60-Hz applications. Continued technological advances in triac device structure has resulted in faster "turn-off" capability and made possible a new family of triacs having 400-Hz commutating capability that is now being offered to circuit designers who must work with 400-Hz source voltages.

Another important parameter for thyristors is the "critical rate of rise of off-state voltage". A source voltage can be suddenly applied to an SCR or a triac which is in the OFF state through either closure of an ac line switch or transient voltages as a result of an ac line disturbance. If the fast rate of rise of the transient voltage exceeds the device rating, the thyristor may switch from the OFF state to the conducting state in the absence of a gate signal. If the thyristor is controlling alternating voltage, "false" turn-on (non-gated) resulting from a transient imposed voltage is limited to no more than half the applied voltage because turn-off occurs during the zero current crossing. However, if the source voltage suddenly applied to the OFF thyristor is a dc voltage, the device may switch to the ON state and turn-off could then be achieved only by circuit interruptions. The switching from the OFF state is caused by the internal capacitance of the thyristor. A steep-rising voltage dv/dt impressed across the terminals of a thyristor causes a capacitance-charging current to flow through the device. This charging current (i=Cdv/dt) is a function of the rate of rise of applied off-state voltage. If the rate of rise of voltage exceeds a critical value,

the capacitance-charging current exceeds the gate trigger current and causes device turn-on. Operation at elevated junction temperatures reduces the thyristor ability to support a steep rising voltage dv/dt because less gate current is required for turn-on. The effect of temperature on the critical rate of rise of off-state voltage is shown in Fig. 14.

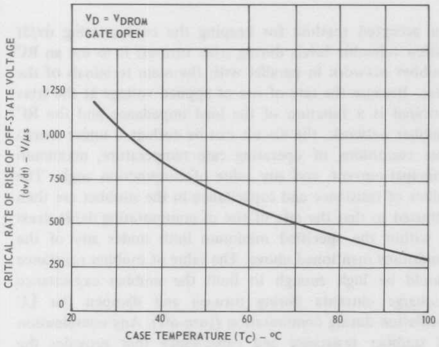

Fig. 14 - Critical rate of rise of off-state voltage as a function of case temperature.

Voltage transients which occur in electrical systems as a result of disturbance on the ac line caused by various sources such as energizing transformers, load switching, solenoid closure, contactors, and the like may generate voltages which are above the ratings of thyristors and result in spike voltages exceeding the critical rate of rise of off-state voltage capability. Thyristors, in general, switch from the OFF state to the ON state whenever the breakover voltage of the device is exceeded, and energy is then transferred to the load. Good practice in the use of thyristors exposed to a heavy transient environment is to provide some form of transient suppression.

For applications in which low-energy, long-duration transients may be encountered, it is advisable to use thyristors that have voltage ratings greater than the highest voltage transient expected in the system to provide protection against destructive transients. The use of voltage clipping cells is also effective. In either case, analysis of the circuit application will reveal the extent to which suppression should be employed. In an SCR application in which there is a possibility of exceeding the reverse-blocking voltage rating, it is advisable to add a clip cell or to use an SCR with a higher reverse-blocking voltage rating to minimize power dissipation in the reverse mode. Because triacs generally switch to a low conducting state, if the di/dt buildup of the principal current flow after turn-on is within device ratings it is safe to assume that reliable operation will be achieved under the specified conditions.

The use of an RC snubber is most effective in reducing the effects of the high-energy short-duration transients more frequently encountered in thyristor applications. When an RC snubber is added at the thyristor terminals, the rate of rise of voltage at the terminals is a function of the load impedance and the RC values used in the network. In some applications, "false" (non-gated) turn-on for even a portion of the applied voltage cannot be tolerated, and circuit response to voltage transients must be determined. An effective means of generating fast-rising transients and observing the circuit response to such transients is shown in Fig. 15. This circuit makes use of the "splash" effects of a mercury-wetted relay to transfer a capacitor charge to the input terminals of a control circuit. This approach permits generation of a transient of known magnitude whose rate of rise of voltage can easily be displayed on an oscilloscope. For a given load condition, the values in the RC snubber network can be adjusted so that the transient voltage at the device terminals is suppressed to a tolerable level. This approach affords the circuit designer with meaningful information as to how a control circuit will respond in a heavy transient environment. The circuit is capable of generating transient

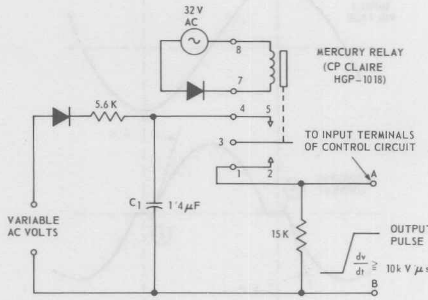

Fig. 15 - Circuit used to generate-fast rising transients.

voltages in excess of 10 kilovolts per microsecond, which exceeds industrial generated transients. The response of a 100-millihenry solenoid control circuit exposed to a fast-rising transient is shown in Fig. 16.

Use of Diacs For Control Triggering

Basically, thryristors are current-dependent devices, and the magnitude of gate current I_{GT} and voltage V_{GT} required to trigger a thyristor into the on-state varies. The point at which thyristor triggering occurs depends not only on the required gate current and voltage, but also on the trigger source impedance and voltage. Fig. 17 shows a family of curves representing the gate-circuit load line between the open-circuit source voltage and the short-circuit current for different time intervals. In a circuit which applies time-dependent variable voltage Vac to a load and the gate trigger current required to trigger the thyristor is derived from the same source Vac, devices that have a gate current I_{gl} are

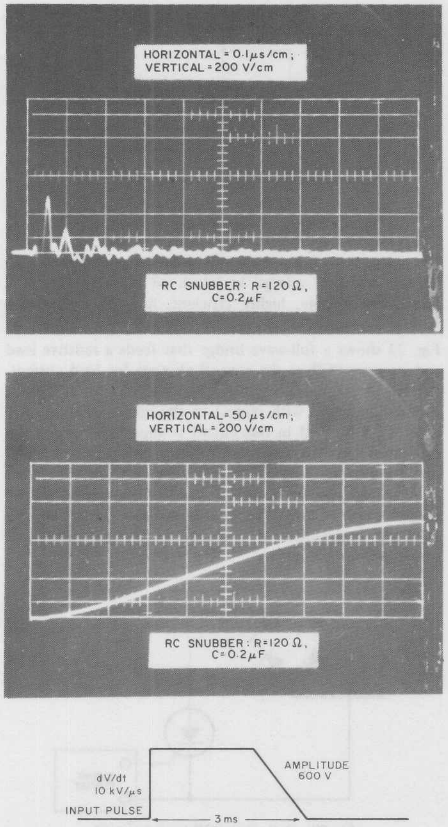

Fig.16 - Waveforms showing response of a 100-millihenry solenoid control circuit to a fast-rising transient.

triggered earlier in the ac cycle than devices that have a higher gate trigger current Fig. 3. Although the circuit is capable of providing variable power to the load, it is heavily dependent on the gate current distribution, and results in uncontrolled conduction angles for a given value of gate series resistance. Furthermore, the circuit does not provide the recommended gate-current overdrive for switching of the fast-rising high-amplitude load currents present in resistive loading. A more efficient circuit for control of variable power to a load that eliminates the need for tight gate-current distribution uses a solid-state trigger device, called a diac, which is voltage dependent.

The diac, often referred to as a bidirectional trigger diode, is a two-terminal, three-layer, transistor-like structure that

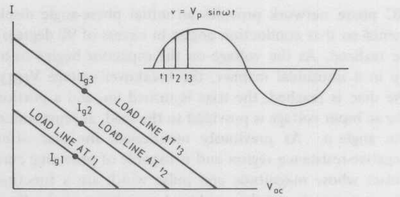

Fig.17 - Thyristor gate-circuit load line for different time intervals.

exhibits a high-impedance blocking state up to a breakover voltage $V_{(BO)}$, above which the device enters a negative-resistance region. The characteristic curve in Fig. 18 shows

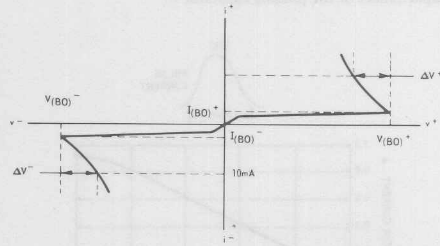

Fig.18 - Diac voltage-current characteristic.

the negative characteristics associated with diacs when they are exposed to voltages in excess of the breakover voltage $V_{(BO)}$. Because of their bidirectional properties and breakover voltage level, diacs are useful in triac control circuits in which variable power is to be supplied to a load. Because of their negative characteristic slope, diacs can also be used with capacitors to provide the fast-rising high-magnitude trigger current pulses recommended in thyristor applications which require efficient gate turn-on for the purpose of switching high-level load currents.

In normal applications, diacs are used in conjunction with RC phase networks to trigger triacs, as shown in Fig. 19. The

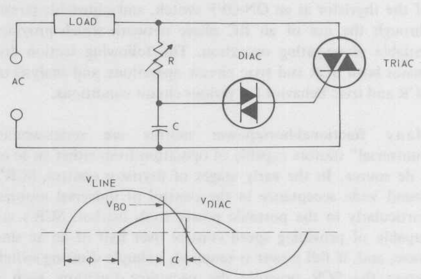

Fig.19 - Use of diac with RC phase network to trigger triac.

RC phase network provides an initial phase-angle displacement ϕ so that conduction angles in excess of 90 degrees can be realized. As the voltage on the capacitor begins to build up in a sinusoidal manner, the breakover voltage $V_{(BO)}$ of the diac is reached, the triac is turned on, and a portion of the ac input voltage is provided to the load, as represented by the angle α. As previously mentioned, the diac offers a negative-resistance region and is capable of providing current pulses whose magnitude and pulse width are a function of the capacitor C and the combined impedance of the diac and the gate and main terminal of the triac. When the voltage on the capacitor C reaches the breakover voltage $V_{(BO)}$, the capacitor does not discharge completely, but is restricted to some finite level as a result of the diac negative-impedance characteristic at high values of pulse current. Fig. 20 shows the peak pulse current of a diac as a function of the capacitances of the phasing capacitor C.

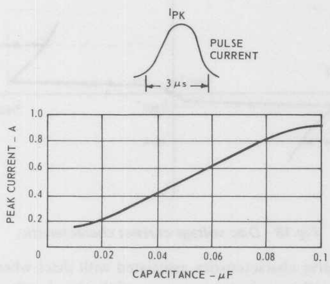

Fig.20 - Peak pulse current of a diac as a function of phasing capacitance.

Power Control Using Thyristors

In the control of ac power by means of semiconductor devices, emphasis has been placed on circuit simplicity, low cost, and small over-all package size. Thyristors meet these goals, and are also capable of providing either fixed or adjustable power to the load. Fixed power is achieved by use of the thyristor as an ON-OFF switch, and adjustable power through the use of an RC phase network which provides variable phase-gating operation. The following section discusses both SCR and triac circuit operations, and analysis of SCR and triac behavior for various circuit conditions.

Many fractional-horsepower motors are series-wound "universal" motors capable of operation from either an ac or a dc source. In the early stages of thyristor control, SCR's found wide acceptance in the control of universal motors, particularly in the portable power tools market. SCR's are capable of providing speed control over half of an ac sine wave, and, if full power is required, a simple shorting switch across the SCR provides the necessary function; such a switch is shown in Fig. 21. Turn-off parameters for this

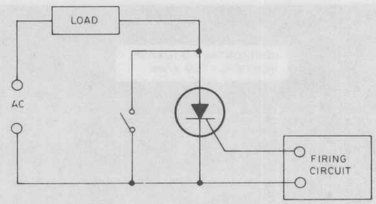

Fig.21 - Simple SCR half-wave control circuit.

circuit are not critical because the SCR has a half-cycle of applied negative voltage in which to recover. The SCR provides a reliable, highly efficient, long-life control for half-wave control circuits.

Fig. 22 shows a full-wave bridge that feeds a resistive load and uses an SCR as the control element for load current. Power control is accomplished by SCR turn-on at various conduction angles with respect to the applied voltage. The criteria for turn-off in this circuit is important because the SCR must recover its forward-blocking state during the time that the forward current stops flowing. Although this time interval may appear to be very small, close analysis of the voltage wave during the transition time in which the full-wave bridge reverses direction reveals that substantial time exists for turn-off.

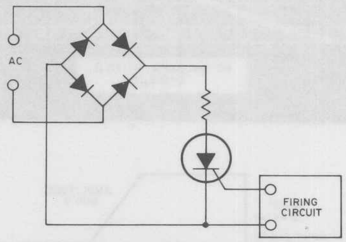

Fig.22 - Full-wave SCR bridge circuit.

Fig. 23 shows one-half of the bridge during the time that the forward current is approaching zero current. Two diodes are in series with the SCR; it is generally accepted that a diode

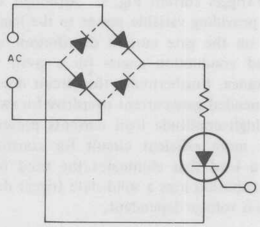

Fig.23 - Half of bridge circuit of Fig. 22 when forward current approaches zero for a resistive load.

voltage of approximately 0.6 volt is required to maintain each diode in conduction. If it is further assumed that a voltage of approximately 0.6 volt is required across the SCR to maintain conduction, the sum of the voltage drops over the circuit requires 1.8 volts; below this value, the SCR drops out of conduction. As the bridge reverses current direction, the same analysis holds true, i.e., forward conduction current is not resumed until the sum of the voltage drops exceeds 1.8 volts.

The waveform during the interval that the voltage wave goes from 1.8 volts to zero can be analyzed by reference to Fig. 24. A half-cycle (180 degrees) of conduction requires 8.3 milliseconds, one degree being equal to approximately 46 microseconds. Because a sine wave is linear for very small angles, a graph can be constructed to show the time interval during which the voltage is less than 1.8 volts for various magnitudes of applied voltage. Analysis of the voltage wave for an angle of one degree shows that an input voltage of 120 volts rms results in a voltage equal to 2.9 volts, which decays to zero in 46 microseconds. Because the SCR is non-conducting below a circuit threshold of 1.8 volts, a time of 28.5 microseconds then elapses while the voltage decays from 1.8 volts to zero. An equal time is required for the bridge to build up to the threshold voltage of 1.8 volts. Therefore, a total exposure time of 57 microseconds elapses in which the SCR is allowed to regain its forward-blocking state.

As shown in Fig. 24, increasing the magnitude of the applied voltage source to 240 volts rms cuts in half the time interval which the SCR is allowed for turn-off. Further increases in input voltage magnitude result in shorter turn-off periods.

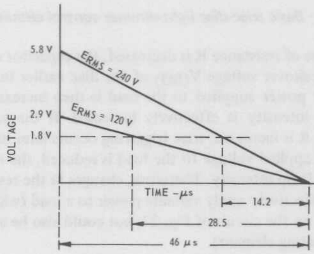

Fig.24 - Waveform of circuit in Fig. 22 as voltage wave goes from 1.8 volts to zero.

This analysis gives a clear, well-defined picture of the turn-off time available for a resistive load. However, for reactive loads, such as fractional-horsepower motors, the turn-off conditions, including turn-off time and dv/dt stress, are more difficult to define because they are affected by a number of variables, including the back EMF of the motor, the ratio of inductance to resistance, the motor loading, and the phase angle of motor current to source voltage. Normally, turn-off times for SCR's are industry-standardized to include peak forward current, rate of rise of reverse current, peak forward blocking voltage applied, and rate of rise of applied blocking voltage. The presence of the applied reverse current helps to shorten turn-off times because the reverse current sweeps out the charge in the blocking junction. For SCR operation from a full-wave bridge in which there is no appreciable reverse voltage available, turn-off is accomplished through recombination, and the effects of circuit loading on SCR operation must be clearly evaluated.

Full-wave ac switching can also be performed by use of two SCR's in an inverse parallel mode, often referred to as a "back-to-back" SCR pair, as shown in Fig. 25. This circuit can be used as a simple static switch or as a variable phase control circuit. It does not make use of a full-wave diode bridge, but simply uses the SCR's in an alternating mode. The circuit has the disadvantage of separate trigger logic, but possesses an inherent advantage in higher-frequency applications because advantage can be taken of the periods of the alternating voltage in which either device may recover to its blocking state. During the half-cycle of the applied voltage that SCR-1 is conducting, SCR-2 is reverse-biased and can recover its blocking state. Because of the applied reverse voltage and associated time of the half-cycle voltage, turn-off times are not critical.

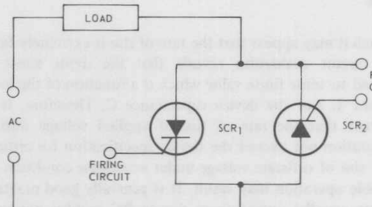

Fig.25 - Full-wave ac switching circuits using a "back-to-back" SCR pair.

This two-SCR circuit is often favored over a triac circuit, even though separate trigger sources are required, because it is supposed to have better commutating capability. Fig. 26 shows the waveforms of commutating dv/dt for the SCR circuit. If the load is inductive with lagging current power factor, the conducting SCR commutates at the time the principal current reaches zero crossover (point A) and reverts to the blocking state; a reapplied voltage of opposite polarity equal to the source voltage then appears across the non-conducting SCR. Because this voltage is a forward-bias voltage to the non-conducting SCR, device turn-on can occur if the rate of rise of applied forward voltage exceeds the device rating for critical rate of rise of off-state voltage. For inductive loading in an inverse-parallel-mode SCR application, power control to the load can be lost if the rate of rise of applied voltage is exceeded.

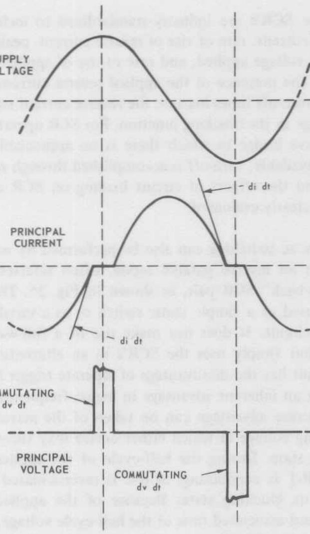

Fig.26 - Waveforms of commutating dv/dt for SCR circuit of Fig. 25.

Although it may appear that the rate of rise is extremely fast, closer circuit evaluation reveals that the dv/dt stress is restricted to some finite value which is a function of the load reactance L and the device capacitance C. Therefore, it is important that the rate of rise of applied voltage during commutation not exceed the device specification for critical rate of rise of off-state voltage under worst-case condition or unreliable operation may result. It is generally good practice in inverse-parallel operation to use an RC snubber network across the SCR pair to limit the rate of rise to some finite value below the minimum requirements, not only to limit the voltage rise during commutation, but also to suppress transient voltage that may occur as a result of ac line disturbances.

As previously mentioned, the use of semiconductor devices for ac power control has emphasized circuit simplicity, low cost, and small over-all package size. The development of the bidirectional triode thyristor, referred to as a triac, achieved all of these goals. Triacs can perform the same functions as two SCR's for full-wave operation, and also simplify gate logic requirements for triggering.

A simple, inexpensive triac circuit that can provide variable power to a load over a full cycle of applied voltage is the light-dimmer circuit. This circuit contains a diac, a triac, and an RC phase-control network. The basic light-dimmer circuit is described below because it provides a good example of triac behavior as related to load requirements and of the operation of a diac in an RC phase-control circuit.

Fig. 27 shows the basic triac-diac light-dimmer control circuit with the triac connected in series with the load. During the beginning of each half-cycle, the triac is in the off-state and the entire line voltage is across the triac; therefore, no voltage appears across the load. (Actually, there is some voltage across the load as a result of triac leakage currents, which are a function of applied voltage and junction temperature. However, these leakage currents are relatively small, at most in the milliampere range, and the resulting load voltages are generally ignored.)

The RC charge-control circuit is in parallel with the control triac, and the applied voltage serves to charge the timing capacitor C through the variable resistor R. When the voltage across C reaches the breakover voltage $V_{(BO)}$ of the diac, the capacitor discharges through the diac and the gate-to-main-terminal-1 impedance of the triac and turns on the control triac. At this point, the line voltage is transferred to the load for the remainder of the applied half-cycle voltage. As the load current reverses direction (zero crossing), the triac turns off and reverts to the blocking state. This sequence of events is repeated for every following half-cycle of applied voltage.

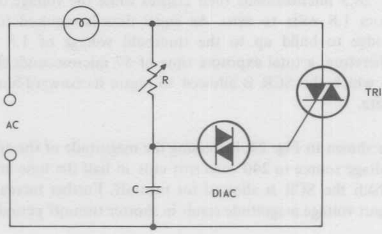

Fig.27 - Basic triac-diac light-dimmer control circuit.

If the value of resistance R is decreased, the capacitor charges to the breakover voltage $V_{(BO)}$ of the diac earlier in the ac cycle; the power supplied to the load is then increased and the lamp intensity is effectively increased. If the value of resistance R is increased, triac triggering occurs later in the ac cycle and applied voltage to the load is reduced; the result is decreased lamp intensity. Therefore, changes in the resistance value R effectively apply variable power to a load (which is a lamp load in the circuit of Fig. 27, but could also be a motor load or heating element).

Although the load is arbitrarily placed in series with main terminal 2, the circuit performs equally as well if the load is shifted to main terminal 1. (Actually, any commercial lamp dimmer available has two wires brought out for external connection, and the chance that the load will be connected to main terminal 1 is 50 per cent.) The only requirements for reliable operation are that the RC phase network be in parallel with the triac and that capacitor-discharge loop currents be directed from the diac to the triac gate and main terminal 1. Although the basic light-control circuit operates

with the component arrangement shown in Fig. 27, additional components are often added to reduce hysteresis effects, extend the effective range of power control, and suppress radio-frequency interference.

Hysteresis in triac phase-control circuits is referred to as the ratio of applied load voltage when the triac initially turns on (as control potentiometer is slowly reduced from some high value) to the value of load voltage prior to "extinguishing" (as the control potentiometer is slowly increased to some higher value). If the circuit has high hysteresis, the control potentiometer travel may be as high as 25 per cent before triac turn-on occurs, after which the control potentiometer may be turned back 15 per cent before the triac "extinguishes". Hysteresis is an undesirable feature if the circuit application requires low-level lamp illumination because a momemtary drop in line voltage may result in the triac "extinguishing" or missing one half-cycle of applied voltage when the capacitor voltage is barely equal to the breakover voltage $V_{(BO)}$ of the diac. If this condition exists, the control potentiometer must be reduced to "start up" the triac again.

Hysteresis is a result of the capacitor discharging through the diac and not recovering the original voltage prior to triggering. Fig. 28 shows the waveforms of the charging

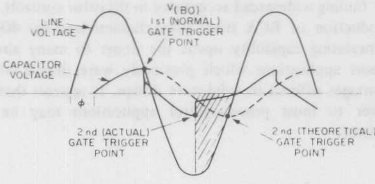

Fig.28 - Charging cycle of capacitor-diac network in Fig. 27 (high hysteresis).

capacitor C as related to the applied line voltage. The initial displacement angle ϕ is a result of the phase angle due to the value of the RC components used. As the value of the control potentiometer is slowly reduced, the value of charging voltage reaches the breakover voltage $V_{(BO)}$ of the diac, and the triac allows that portion of the ac wave remaining to appear at the load, as represented by the shaded area at the first trigger point. At this point, there is an abrupt change in capacitor voltage (Δ V). Therefore, as the capacitor charge reverses direction, the second trigger point is reached much earlier in the next half-cycle, and that portion of the ac wave remaining appears across the load, as represented by the shaded area at the second trigger point. The second trigger point and subsequent trigger points represent the steady-state level at which triggering occurs. Some reduction in hysteresis can be realized by inserting a resistor in series with the diac to reduce the effective diac negative resistance and minimize the change in capacitor voltage. However, this change reduces the gate current pulse and, if not carefully controlled, may result in di/dt failures because the triac switches high-magnitude current under minimum gate drive.

A more effective method of reducing hysteresis is to use a second RC time constant, or a "double-time-constant" circuit such as that shown in Fig. 29. As C_2 supplies the

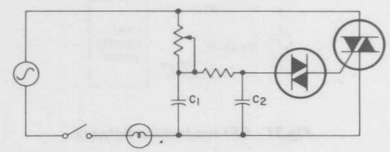

Fig.29 - "Double-time-constant" light-control circuit.

charging voltage for the diac breakover voltage $V_{(BO)}$, the abrupt change is capacitor voltage during diac turn-on is partially restored by capacitor C_1, as shown in Fig. 30. The restoring of the charge on C_2 maintains the original triggering point very closely and results in extended range of the control setting. This triac circuit can be turned on for very low levels of applied voltage and is not prone to "extinguishing" for line-voltage drops.

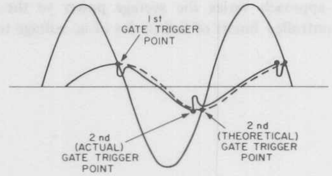

Fig.30 - Charging cycle of capacitor-diac network in Fig. 29 (reduced hysteresis).

Because triac switching from the high-impedance to the low-impedance state can occur in less than one microsecond, the current applied to the load increases from essentially zero to a magnitude limited by the load impedance within the triac switching time. This rapid rise of load current produces radio-frequency interference (RFI) extending into the range of several megahertz. Although this rapid rise does not affect television and FM radio frequencies, it does affect the short-wave and AM radio bands. The level of RFI generated is well below that caused by small ac/dc brush-type motors, but some means of RFI suppression is generally required if

the triac phase-control circuit is to be used for any extended period of time in an environment in which RFI generation cannot be tolerated.

A reasonably effective suppression technique is shown in Fig. 31. An inductor is connected in series with the triac control circuit to restrict the current rate of rise, and a filter capacitor is used in parallel with the entire network to bypass high-frequency signals.

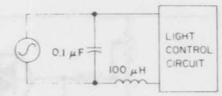

Fig.31 - RFI-suppression network.

The values shown in Fig. 31 are effective in reducing RFI noise for rms load currents up to 6 amperes to such an extent that the effects on short-wave and AM signals are either minimized or considered tolerable. For values above 6 amperes rms, additional suppression can be achieved by use of dual chokes in the ac lines to the triac network. Depending on the circuit performance required, such suppression may or may not be effective and other means of triac control may be required.

An alternate method of providing high-current heating controls is through use of a proportional control circuit using integral-cycle synchronous switching or zero-voltage switching. This approach varies the average power to the load through controlled bursts of full cycles of ac voltage to the load by turning on the triac at the beginning of the zero-voltage crossing. Because the triac turns on near zero current, the sudden current steps associated with phase control circuits and the RFI generated are minimized. The RCA-CA3059 zero-voltage switch is a monolithic integrated circuit used primarily as a trigger-current generator for control of thyristor turn-on during the zero-voltage transition. This circuit has many features, one of which is a fail-safe circuit which inhibits output pulses in the event that the external sensor is opened or shorted.

Conclusions

This Note has reviewed thyristors from the viewpoints of temperature and voltage conditions, gate trigger characteristics, and effects of SCR's and triacs on circuit performance. The availability of power thyristors gives design engineers greater freedom in achieving circuit simplicity, low cost, and small package assembly than electromechanical or tube counterparts. Technological improvements are far from reaching the saturation level, but are opening new doors for circuit application. The impact of thyristor applications is being felt in normal everyday environments such as residential lamp dimming, TV deflection systems, home appliances, marine ignition, automotive applications, electric heating, comfort controls, and igniters for fuel-fired furnaces. Industrial applications for multiple-horsepower motors, lamp display boards, inverters, relay protection or replacement, radar, sonar, and emergency standby generating systems are now finding widespread acceptance in thyristor controls. The introduction of RCA triacs fully characterized for 400-Hz commutating capability opens the doors to many aircraft support applications which previously were devoid of the advantages offered in solid-state design. It appears that the answer to most power-control applications may be the thyristor.

When incorporating RCA Solid State Devices in equipment, it is recommended that the designer refer to "Operating Considerations for RCA Solid State Devices", Form No. 1CE-402, available on request from RCA Solid State Division, Box 3200, Somerville, N. J. 08876.